



METHOD AND COMPOSITIONS TO
ASSESS OXIDATIVE STRESS IN VIVO

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Lisa R. Mueller
(Typed or printed name of person mailing paper or fee)

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(Signature of person mailing paper or fee)

L. Jackson Roberts
Jason D. Morrow



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ASSESS OXIDATIVE STRESS IN VIVO

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- A 5 This application is a continuation-in-part of U.S.
Serial No. 07/715,419 filed June 14, 1991. *now abandoned*

BACKGROUND OF THE INVENTION

10 Field of the Invention

This invention relates to a method to assess
oxidative stress in vivo by quantification of
prostaglandin-like compounds and their metabolites
produced by a noncyclooxygenase free radical
15 catalyzed mechanism.

Background of the Invention

Free radicals derived primarily from oxygen
have been implicated in the pathophysiology of a
20 number of human diseases, such as atherosclerosis,
ischemia-reperfusion injury, inflammatory diseases,
cancer and aging. A variety of methods have been
developed to assess oxidative stress; however, some
of these methods have limited sensitivity or
25 specificity, while others are either too invasive
or not adaptable for human investigation.

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Halliwel, B., et al. The Measurement Of Free Radical Reactions In Humans: Some Thoughts For Future Experimentation. FEBS Letters. 213:9-14, 1987.

5 Free radicals are generally short lived and thus, indirect methods of detection are required. Pryor, W., On The Detection Of Lipid Hydroperoxides In Biological Samples, FREE RADICAL BIOLOGY & MEDICINE, Vol. 7, pages 177-178, 1989. Standard
10 detection methods include: electron spin resonance (directly), electron spin resonance (spin trapping), thiobarbituric acid reactive substances (TBARS), detection of malonaldehyde by direct methods (such as HPLC of malonaldehyde itself or as
15 its dinitrophenylhydrazone), detection of other oxidation products from polyunsaturated fatty acids (such as 4-hydroxynonenal), measurement of lipid hydroperoxides, detection of volatile hydrocarbons (ethane, pentane and ethylene), detection of
20 oxidation products from lipids other than polyunsaturated fatty acids (e.g., cholesterol), oxidation of methional, methionine, or 2-keto-4-thiomethylbutanoic acid to ethylene, oxidation of benzoic acid to carbon dioxide (often with

radiolabelled carbon dioxide), oxidation of phenol, benzoic acid, or aspirin to hydroxylated products, determination of decreases in antioxidant levels (e.g., decreased GSH, tocopherol, or ascorbate) or
5 of increases in the oxidized products from antioxidants (e.g., tocopherol quinone or the ascorbyl radical), detection of oxidized DNA bases (e.g., thymine glycol, 8-hydroxydeoxyguanosine), detection of oxidized products from proteins (e.g.,
10 methionine sulfoxide from methionine) or of proteins oxidized to carbonyl-containing products that then react with hydride-reducing agents, detection of adducts of DNA bases (e.g., by enzymatic hydrolysis post-labeling using P32), and
15 chemiluminescence methods. Id.

Unfortunately, oxidative stress is difficult to assess in humans due to lack of reliable methods to assess oxidant stress in vivo. As one author stated, "one of the greatest needs in the field now
20 is the availability of a non-invasive test to probe the oxidative stress status of humans." Id.

Morrow et al. discovered that a series of prostaglandin F₂-like compounds, now termed F₂-isoprostanes, were generated in human plasma during

storage at -20°C for several months or in plasma that had been repeatedly frozen and thawed. Morrow et al., "Noncyclooxygenase Oxidative Formation of a Series of Novel Prostaglandins: Analytical
5 Ramifications for Measurement of Eicosanoids", Anal. Biochem. 184:1-10(1990). Morrow et al. determined that these compounds were formed by a non-cyclooxygenase mechanism by autoxidation of arachidonic acid contained in plasma. This article
10 demonstrated that prostaglandins could be generated by autoxidation during storage of biological samples which could result in artifactual results with measurements of prostaglandins in stored samples. At that time, there was nothing to
15 suggest that this was anything more than just a non-enzymatic in vitro artifact or phenomenon that occurred during the storage of plasma or other lipid containing biological fluids. In fact, this process, autoxidation of lipids or fats, is a major
20 process responsible for spoilage of food during storage.

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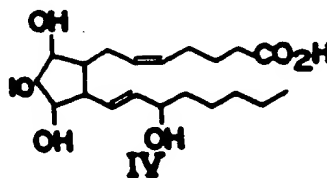
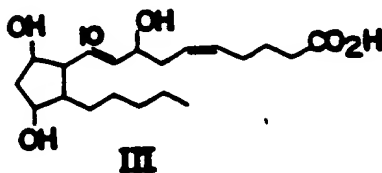
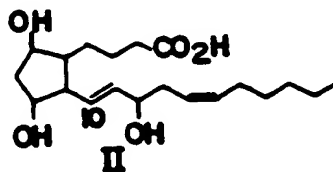
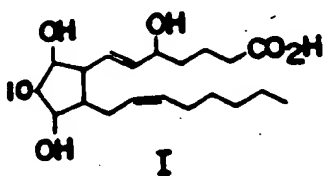
SUMMARY OF THE INVENTION

This invention is based on the discovery that prostanoids, particularly prostaglandin F₂-like compounds, are produced in vivo by a

5 noncyclooxygenase free radical catalyzed mechanism. More specifically, it has been found that the quantity of free prostaglandin F₂-like compounds in plasma and urine increases in response to agents that cause free radical induced lipid peroxidation.

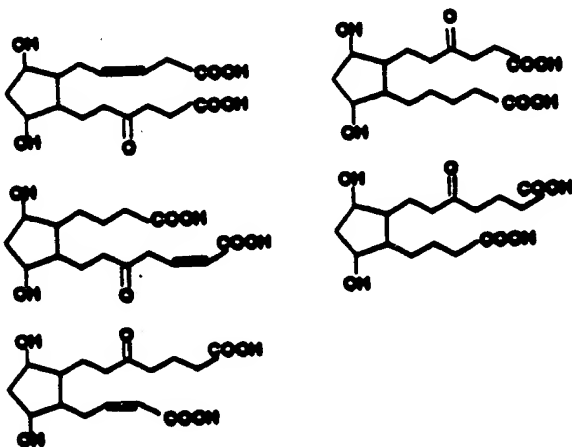
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These prostaglandin F₂-like compounds are isomeric to prostaglandins produced by the cyclooxygenase enzyme and are now referred to as F₂-isoprostanes. The prostaglandin F₂-like compounds
15 produced in response to said free radical induced lipid peroxidation having the following basic structures. Each of the four structures shown are comprised of eight racemic diastereomers:



Another embodiment of this invention involves the discovery that the levels of metabolites of prostaglandin F₂-like compounds also increase in response to oxidative stress. The metabolites of prostaglandin F₂-like compounds produced in response to said free radical catalyzed mechanism have the following formula:

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Still another embodiment involves the discovery that human tissue samples could be analyzed for prostaglandin F₂-like compounds.

Based on these discoveries, this invention can be used to provide a reliable method to assess oxidative stress in vivo in humans by quantifying prostaglandin F₂-like compounds and their

metabolites. In particular, this invention provides a method to assess oxidative stress in vivo by obtaining a fresh sample of biological fluid or tissue, measuring the amount of

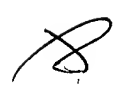
5 noncyclooxygenase derived prostanoid compounds in the sample, comparing the measured amounts of the prostanoids with a control and assessing the oxidative stress in vivo based upon said comparison. It is an object of this invention to

10 quantify these prostanoid compounds in various biological fluids including: plasma, urine, cerebrospinal fluid, bile, lung lavage fluid, lymph, and inflammatory human joint fluid. If the sample contains lipids, the measurement of

15 noncyclooxygenase derived prostanoid compounds should be made prior to the ex vivo formation of prostaglandin F₂-like compounds.

Additionally, this invention provides a method to assess oxidative stress in vivo by measuring the

20 amount of noncyclooxygenase derived metabolites of prostanoids in a fresh sample, comparing the measured amount of the metabolites of prostanoids with a control and assessing the oxidative stress in vivo.



This invention also provides a substantially pure composition of the formula of Fig. 2. This invention may be used to assess oxidative stress in humans and it is also useful as a test for the utility of drugs such as LAZAROIDs (Upjohn Co.).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows noncyclooxygenase free radical catalyzed mechanism for the formation of prostaglandin F₂-like compounds and the chemical structure of four regioisomers.

FIG. 2 shows the chemical structure of noncyclooxygenase derived prostaglandin F₂-like urinary metabolites.

FIG. 3A & 3B show possibilities of stereochemical changes of hydroxyls and side chains of the metabolites shown in FIG. 2.

FIG. 4 shows selected ion current chromatogram obtained from the analysis of prostaglandin F₂-like compounds in normal human urine. Below is the m/z 576 peak representing the (²H₇)9 α ,11 β -prostaglandin F₂ internal standard. At the top is the m/z 569 chromatogram which reveals a series of peaks representing endogenous urinary prostaglandin F₂-

like compounds. Levels of the individual compounds range from approximately 500 to 3000 picograms/mL.

DETAILED DESCRIPTION OF THE INVENTION

5 Prostaglandin F₂-like compounds are produced in vivo by a noncyclooxygenase free radical catalyzed mechanism. Free prostaglandin F₂-like compounds have been quantitated in plasma and urine. The level of individual prostaglandin F₂-like compounds
10 in plasma ranges from approximately 5 - 50 picograms/mL and in urine from approximately 500 - 3000 picograms/mL.

The prostaglandin F₂-like compounds are produced in vivo by free radical catalyzed
15 mechanism. In particular, electron ionization mass spectra analysis of human urine shows four prostaglandin F₂-like regioisomers. FIG. 1.

The quantity of free prostaglandin F₂-like compounds in plasma or urine increases in response
20 to agents that cause free radical induced lipid peroxidation. Circulating levels of the compounds were shown to increase by as much as 200-fold in animal models of free radical induced lipid peroxidation. The herbicide diquat undergoes redox

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cycling in vivo leading to the production of superoxide anions. When diquat is administered to Se-deficient rats, marked lipid peroxidation ensues. Circulating levels of prostaglandin F₂-like compounds in plasma obtained 1½ hours following administration of diquat to eight Se-deficient rats were dramatically elevated from 27 to 200-fold above levels measured in Se-deficient control rats that did not receive diquat. The pattern of the elevated prostaglandin F₂-like compounds in treated rats also was essentially identical to the pattern seen in untreated rats.

The second animal model employed administration of carbon tetrachloride to normal rats. This leads to the formation of CCl₃• radicals which catalyze lipid peroxidation. Treatment of six rats with carbon tetrachloride also resulted in marked increases in the circulating levels of prostaglandin F₂-like compounds ranging from 10 to 30-fold above normal. In addition, pretreatment of the rats with high doses of indomethacin to inhibit cyclooxygenase activity failed to suppress the production of these compounds following administration of carbon tetrachloride.

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Collectively, the above results have established that there are a unique class of prostanoids that are produced in vivo by a noncyclooxygenase mechanism involving free radical catalyzed lipid peroxidation.

It should be understood that it is possible that prostaglandin D₂-like and prostaglandin E₂-like compounds may form from isomerization of prostaglandin G₂-like endoperoxide intermediates in aqueous solutions. Incubation of human plasma ex vivo yields significant amounts of prostaglandin D₂-like and prostaglandin E₂-like compounds when analyzed by gas chromatography selected ion monitoring negative ion chemical ionization mass spectrometry. Recently, the inventors have obtained evidence that noncyclooxygenase derived prostaglandin D₂-like and E₂-like compounds are present acylated to liver phospholipids in vivo.

Since the quantity of free prostaglandin F₂-like compounds in human plasma or urine increases in response to agents that cause free radical induced lipid peroxidation, an assay to measure oxidative stress in vivo may be devised. Prostaglandin F₂-like compounds may facilitate this

analysis because they are easily detected in normal human biological fluids.

Prostaglandin F₂-like compounds may also participate as mediators in the pathophysiology of oxidative stress. Thus, substantially purified prostaglandin F₂-like compounds or an antagonist of these compounds may be useful in the treatment of oxidative stress related diseases.

One drawback discovered relating to the use of these free prostaglandin F₂-like compounds as a means to assess oxidative stress is the ex vivo generation of prostaglandin F₂-like compounds in certain biological fluids. Arachidonyl containing lipids in plasma readily undergo peroxidation in vitro leading to the formation of these prostanoids. The inventors have found that plasma can be allowed to stand at room temperature for up to two hours without levels of these compounds increasing significantly. However, these compounds can be generated in substantial quantities if plasma is allowed to stand for longer periods of time, if plasma is frozen and thawed several times, or if plasma is subjected to storage at -20°C for periods of time such as a few weeks. The problem

of artifactual generation of these compounds can be minimized, but not totally eliminated, by addition of antioxidants to the sample. Thus, to avoid these potential sources of error, plasma that is
5 obtained for analysis should not be stored and should be processed for analysis within approximately two hours. However, it is not necessary to process the plasma sample completely through the assay. Plasma phospholipids containing
10 arachidonic acid are the lipid source for which these compounds are generated ex vivo. Although phospholipids are generally retained by C-18 reverse phase chromatography packing, the inventors have found that phospholipids in plasma are not,
15 presumably due to binding to plasma proteins. Thus, when plasma is initially subjected to solid phase extraction using a C-18 cartridge, free prostaglandin F₂-like compounds present in the plasma are retained and the phospholipids are
20 quantitatively removed in the initial aqueous phase elute. After the retained prostaglandin F₂-like compounds are eluted with a 1:1 mixture of ethyl acetate:heptane, they can be stored at -20°C and processed later without the problem of ex vivo

generation. The inventors have also recently found that whereas these prostaglandins are generated ex vivo in plasma during storage at -20°C , formation of these compounds did not occur while the plasma was stored for five months at -70°C .

The above discussed problem surrounding plasma undoubtedly applies to any biological fluid which contains significant quantities of lipids which can be the source of ex vivo generation of these prostanoids. This problem however is not encountered with analysis of urine. Urine contains very few lipids and the inventors have found that the levels of prostaglandin F_2 -like compounds do not increase during storage of urine for up to six months at -20°C or during incubation of urine for seven days at 37°C . However, there is a potential problem associated with the quantification of these compounds in urine as an index of their systematic production. At present, the inventors do not know the primary source from which the compounds present in urine are derived. Specifically, it is not known if they originate primarily from plasma via filtration by the kidney or if they arise primarily from local production in the kidney. Urinary

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cyclooxygenase derived prostaglandins have been shown to arise almost exclusively from local formation in the kidney. If this is also the case with the noncyclooxygenase derived prostanoids, then quantification of these compounds in urine could be used to assess oxidant stress in the kidney but this approach could not be used as an index of their systemic production.

Recently, however, the inventors have obtained data which may provide a new dimension on the ability to assess endogenous production of these compounds which circumvents the above discussed problems. In the process of developing a mass spectrometric assay for the major urinary metabolite of cyclooxygenase derived prostaglandin D_2 , the inventors have identified urinary metabolites of these noncyclooxygenase derived prostaglandin F_2 -like compounds in human urine. The metabolites have the same basic atomic composition as the prostaglandin D_2 metabolite ($9\alpha, 11\beta$ -dihydroxy-15-oxo-2,3,18,19-tetranorpropane-1,20-dioic acid), but are structurally different. See Figs. 3A & 3B and 4. The levels of metabolites of the noncyclooxygenase derived F_2 -like compounds are

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not suppressed by treatment with cyclooxygenase inhibitors. Additionally, it has been found that metabolite levels increase significantly in urine following administration of carbon tetrachloride to rats. The ability to quantify a metabolite of these compounds would be extremely valuable in that it would provide an index of systemic production of these compounds without the inherent potential problem of artifactual generation of the compound ex vivo.

Still another alternative embodiment involves a discovery that tissue samples could also be analyzed for prostaglandin F_2 , D_2 and E_2 -like compounds. This observation was unexpected and surprising. Arachidonic acid is the precursor of both enzymatically derived prostaglandins and the prostaglandin F_2 -like compounds formed by non-enzymatic peroxidation of arachidonic acid. Arachidonic acid is almost entirely stored esterified to tissue phospholipids, with only small amounts being present in free form in cells.

In enzymatic formation of prostaglandins, arachidonic acid has to be released from phospholipids by phospholipases to be metabolized

by the cyclooxygenase enzyme to form
prostaglandins. Once the enzymatically formed
prostaglandins are produced, they are released from
cells and not stored and are not found esterified
5 to phospholipids in tissues. Thus, tissue levels
of prostaglandins are essentially unmeasurable.

When phospholipids are subjected to oxidation,
it is known that fatty acid hydroperoxides are
formed on the phospholipids. These hydroperoxides
10 have been shown to be readily cleaved from
phospholipids by phospholipases. One question the
inventors investigated was whether, in contrast to
cyclooxygenase derived prostaglandins, the
prostaglandin F_2 -like compounds are formed intact on
15 phospholipids during free radical catalyzed
peroxidation of lipids or whether only the oxidized
precursors, i.e. the fatty acid hydroperoxides, are
formed on phospholipids which are then cleaved by
phospholipases and subsequently undergo the further
20 transformation to yield prostaglandin F_2 -like
compounds. Experiments were carried out which
provided direct evidence that the prostaglandin F_2 ,
 D_2 , and E_2 -like compounds are actually formed in
situ esterified to phospholipids and that the

levels of the compounds esterified to phospholipids in tissues of the rat following administration of CCl_4 to induce lipid peroxidation increased dramatically compared to levels in tissues of untreated rats.

These findings suggest another approach to assess oxidant status in tissues in some human disorders. The sensitivity of the method of detection allows the inventors to detect prostaglandin F_2 -like containing phospholipids in very small pieces of tissue well within the amount of tissue that would ordinarily be obtained in a routine biopsy. Biopsies of a variety of tissues are routinely obtained for the diagnosis of numerous types of human diseases. For example, a number of liver diseases including alcohol liver damage are speculated to involve free radical induced injury. One problem that we have recognized with measuring levels of free compounds in plasma or urine or their metabolites is that local formation of these compounds at a limited site in the body may not be associated with the release of free compounds in quantities sufficient to significantly elevate the basal levels that we

see in plasma or urine in normal humans. In these situations it may require sampling of blood draining directly from the site of suspected pathophysiology. This can be very impractical
5 and/or impossible in many situations in humans. However, if a biopsy is obtained of an involved tissue or organ, this approach may allow us to directly assess oxidant status in the biopsy tissue by measuring the level of prostaglandin F_2 -like
10 compounds esterified to tissue phospholipids. This approach could therefore be used to directly obtain evidence for the occurrence of free radical induced injury in the pathophysiology of a wide variety of human diseases.

15 One possible method to detect the quantity of prostaglandin F_2 -like compounds in biological fluids is mass spectroscopy. This type of assay for prostaglandin F_2 -like compounds or their metabolites offers several advantages: First, the mass
20 spectrometric assay is very sensitive with a lower limit of detection in the range of 1 picogram. Second, the assay has a high degree of specificity and accuracy.

The present method is a stable isotope dilution assay employing capillary gas chromatography negative ion chemical ionization mass spectrometry. Heptadeuterated $9\alpha,11\beta$ -
5 prostaglandin F_2 or deuterated prostaglandin $F_2\alpha$ is used as the internal standard. Prostaglandin F_2 -like compounds are extracted by solid phase techniques using a C-18 cartridge and subsequently purified by thin layer chromatography. Analysis by
10 mass spectrometry is accomplished as a pentafluorobenzyl ester, trimethylsilyl ether derivative. Quantification is performed by selected ion monitoring of the ratio of the M-181 (loss of oCH_2C_6F_6) ions at m/z 569 for endogenous
15 prostaglandin F_2 -like compounds and m/z 576 for the internal standard. The assay has a precision of $\pm 6\%$ and an accuracy of 96%. Lower limits of detection are in the range of approximately 1 picogram. See Fig. 4.
20 The basic assay can be employed and adapted for measurement of these compounds in a wide variety of biological fluids. In addition to plasma and urine, the assay can be used with

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cerebrospinal fluid, bile, lung lavage fluid, lymph, and inflammatory human joint fluid.

In an alternative embodiment, the prostaglandin-like compounds can be assayed using immunoassays. Immunoassay is a suitable method for the detection of small amounts of specific prostanoids (5-500 picograms can be readily detected). In particular, antibodies can be raised to these prostaglandin-like compounds using conventional techniques. The antibodies can then be used in immunoassays to quantitate the amount of prostaglandin-like compounds in the biological fluid.

A small molecule (less than 5-10 kilodaltons) will usually not elicit the production of antibodies in experimental animals unless covalently linked to large immunogenic molecules prior to immunization. The noncyclooxygenase derived prostaglandin-like compound, such as, 8-epi-prostaglandin $F_2\alpha$ can be coupled via its carboxyl group to a carrier protein by the dicyclohexyl-carbodiimide method. Rich, D.H., et al., The Peptides, 1:241-261 (1979); U.S. Patent No. 4,859,613. 8-epi-prostaglandin $F_2\alpha$ can be

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coupled to keyhole limpet hemocyanin (KLH) by the DCC method used by Levine et al. 1980, Prostaglandins 20: 923-934. Accordingly, 8mg. of 8-epi-prostaglandin $F_2\alpha$ are dissolved in 100 μ l of

5 N,N-dimethyl formamide. The 8-epi-prostaglandin $F_2\alpha$ is then activated by the addition of 3mg of DCC in the presence of 3.5mg. of N-hydroxysuccinimide as a trapping agent. This reaction mixture is stirred for 30 minutes at room temperature. As the

10 reaction proceeds the byproduct dicyclourea will form a white precipitate. When the reaction is complete, this precipitate is removed by centrifugation. The supernatant is then added to 6.25 gm of KLH in 0.5ml of 0.1N NaHCO_3 and stirred

15 for 2 hours at 4°C. The conjugate is then extensively dialyzed against PBS, pH 7.5 (0.15M NaCl, 0.005M NaHPO_4). The conjugate is aliquoted and stored at -20°C. It should be noted that many unsaturated fatty acids and their derivatives, are

20 sensitive to oxidation. However, this does not hold for prostanoids which have only a single double bond on each side chain. Prostaglandin F_2 -like compounds are extremely stable, can withstand strong base and strong acid and are not susceptible

to oxidation. Hence, although there is no facile method by which to determine the integrity of the 8-epi-prostaglandin $F_2\alpha$ haptens attached to KLH, it is unlikely to undergo degradation or modification that could impede the production of specific antisera.

These immunogens can then be used to raise antibodies. Rabbits can be immunized with the 8-epi-prostaglandin $F_2\alpha$ -KLH conjugate administered in Complete Freund's Adjuvant. One immunization dosing and scheduling is as follows: 100 μ L of conjugate in Complete Freund's Adjuvant will be administered at multiple subcutaneous sites for the primary immunization. At subsequent two week intervals 100 μ L of conjugate in Incomplete Freund's Adjuvant will be administered at multiple subcutaneous sites to boost titers. Serum will be collected from animals one week following the initial boost and titers will be determined by ELISA. Similarly, myeloma that secrete monoclonal antibodies can be prepared following the techniques described by Kohler & Milstein (1975).

These antibodies can be used in immunoassays for noncyclooxygenase derived prostaglandin-like

compounds. Typical assays for these types of compounds include enzyme-linked immunoassays, fluorescent immunoassays, and radioimmunoassays. The assays can be in the sandwich or competitive
5 formats. See, e.g., David, U.S. Patent Nos. 4,376,110 and 4,486,530.

Example 1 Mass spectroscopic assay for prostaglandin F₂-like compounds in urine. (Fig 4)

1 mL of fresh human urine was analyzed in a
10 stable isotope dilution assay for endogenous prostaglandin F₂-like compounds. At the bottom of each chromatogram is the m/z 576 peak representing the internal standard. At the top of each tracing are the m/z 569 chromatograms which reveal a series
15 of peaks presumably representing endogenous prostaglandin F₂-like compounds. See Fig. 4. The levels of the individual compounds in plasma range from approximately 5-50 picogram/ml and in urine from approximately 500-3000 picogram/ml. Employing
20 a variety of approaches, including electron ionization mass spectral analysis of these compounds from 1 liter of human urine, it was firmly established that these peaks indeed

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represented regioisomers of prostaglandin F₂-like compounds shown in Figure 1.

Administration of high doses of cyclooxygenase inhibitors to normal volunteers failed to suppress
5 the levels of these compounds measured in fresh normal human plasma and urine, indicating that their formation occurs independent of cyclooxygenase activity. Further studies established that the levels measured in fresh
10 plasma and urine do not arise from ex vivo formation in that the presence of antioxidants in the specimen collecting containers did not suppress the levels measured and levels in urine did not increase during incubation for several days at 37°C
15 or during storage for up to 6 months at -20°C. In addition, levels were not suppressed by a diet consisting solely of glucose polymers, indicating that these compounds do not arise from dietary sources.

20 While the present invention has been described by reference to certain illustrative examples, various modifications and variance within the spirit and scope of the invention will be apparent to those skilled in the art.

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